A Peculiar Burst of Stars

Livermore astrophysicists find evidence that radio jets emitted from black holes give rise to new stars.

LOOKING up to the vast expanse of the sky on a clear night, stargazers see a showy sparkle of planets, stars, and galaxies. And for every celestial body they can see, countless more escape view.

Advanced technologies allow today's astronomers to visualize heavenly bodies that past astronomers—from Hipparchus and Aristarchus to Galileo and Kepler—could not have imagined. However, even with the most powerful optical telescopes, they do not get the whole picture.

What they cannot see in this astral show are details of galaxies, supernovas, distant quasars, and other objects that emit electromagnetic radiation at wavelengths outside the region of visible light. Many celestial objects emit radio waves—electromagnetic radiation with a wavelength much greater than that of visible light. (See the box on p. 13.) Scientists have found that by capturing the emitted signals with radio telescopes and studying the sky with optical telescopes, they can piece together a more complete picture of the astrophysical phenomena at work in the universe. (See the box on p. 15.)

Astrophysicists Wil van Breugel and Steve Croft at Livermore's branch of the University of California's Institute for Geophysics and Planetary Physics are using this radio astronomy technique to examine black holes and the gas jets that emanate from them. Their research indicates that these radio jets may trigger the formation of new stars.

Finding the Invisible

Van Breugel and his team are studying a starburst system called Minkowski's Object near the NGC 541 radio galaxy. This arc of perhaps 10 million stars, which spans 32,000 light years, may have originated in the warm, "clumpy" gas at the edge of the galaxy's radio jet. The idea that radio jets induce star formation is relatively new. Several decades ago, when astronomers discovered the first radio jet associated with a galaxy, they believed the pairing was caused by a chance contact with an older galaxy. "Researchers had a lot of theories about what was going on but no evidence to support them," says van Breugel. Today, with optical charge-coupled devices and a new generation of powerful radio telescopes, scientists can acquire more detailed data, and this new evidence is helping to shape their conclusions.

In the late 1990s, van Breugel and his team developed an efficient method using radio sources to pinpoint extremely distant galaxies. In 2000, as part of a Laboratory Directed Research and Development (LDRD) project, they used this technique to find radio galaxies in the early universe. In the process, they discovered the most distant radio galaxy known to date—powered by an active black hole or quasar 12.4 billion light years away. With this method, researchers can investigate how galaxies form and determine the role played by supermassive black holes.

This false-color image of Minkowski's Object is a composite of three images—two taken in visible light by the Hubble Space Telescope (the blue and green channels) and one taken in infrared light by a telescope at the W. M. Keck Observatory (the red channel). The blue colors of the young stars in Minkowski's Object contrast with the older double star nearby and a faint background galaxy (red).

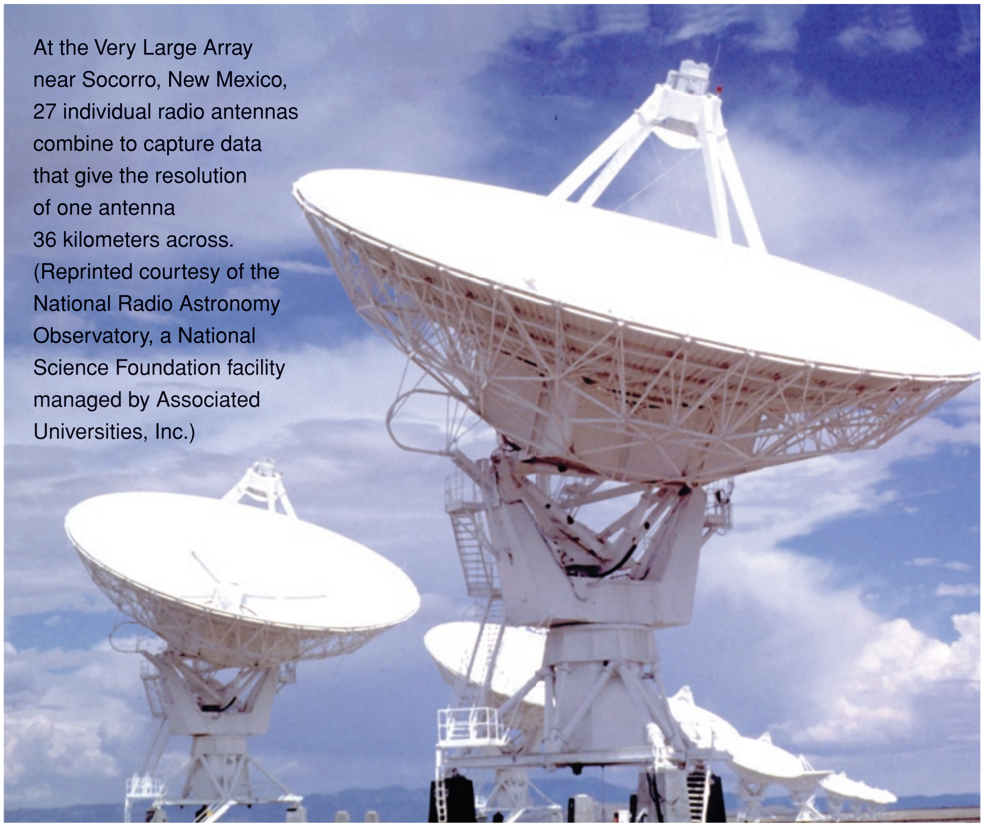
To examine the NGC 541 radio galaxy, van Breugel and Croft combined data from the Very Large Array radio telescope near Socorro, New Mexico; the Hubble Space Telescope (HST); and one of the twin telescopes operated by the W. M. Keck Observatory and located at the summit of Hawaii's dormant Mauna Kea volcano. NGC 541 is relatively close to Earth, at just 216 million light years away. Van Breugel and Croft wanted to determine if the peculiar burst of stars they had observed was a rejuvenated older galaxy or a completely newborn colony of stars.

Images and spectra of Minkowski's Object taken by HST and the Keck telescopes in both the infrared and optical regions indicate that the system contains young stars—a mere 10 million years old. Because of this finding and similar discoveries of jet–galaxy pairings, the collocation of Minkowski's Object and the radio jet no longer seems to be a chance happening. Researchers now believe that black holes and the radio jets that shoot out of them are likely triggering star formation.

A Star Is Born

This star formation process, in which radio jets cause interstellar gas clouds to collapse and form new stars, is relatively rare today. But the phenomenon may have been more common and significant in creating galaxies in the early universe. Much more hydrogen gas would have been available then because relatively few stars and galaxies had consumed it earlier during their formation. Black holes were also more active. "This certainly isn't the dominant way stars are formed," says Croft, "but the conditions we observe around Minkowski's Object do not appear to be exceptional."

Normally, stars form from the collapse of cold, molecular gas clouds. When warm, dense gas is abundant in the interstellar medium—the region between stars—the violent matter and energy of the radio jets could collide with the gas, compressing the clouds and causing them to cool faster than usual. This cooling, in turn, hastens the process of star formation. Van Breugel's observations of NGC 541 agree with this hypothesis. The team's research shows that when a radio jet collides with warm, dense hydrogen near the parent galaxy, the medium begins to cool and forms a large neutral hydrogen cloud from which stars are subsequently born. Radio waves emitted by this cloud provide key data, but optical instruments cannot detect such long wavelengths.



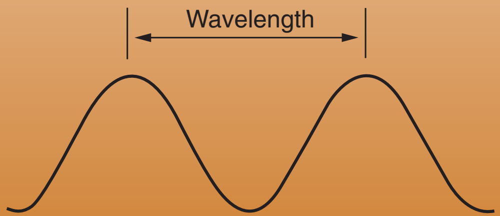
At the Very Large Array near Socorro, New Mexico, 27 individual radio antennas combine to capture data that give the resolution of one antenna 36 kilometers across. (Reprinted courtesy of the National Radio Astronomy Observatory, a National Science Foundation facility managed by Associated Universities, Inc.)

The Electromagnetic Spectrum: From Radio Waves to Gamma Rays

Radio waves, visible light, x rays, and all the other parts of the electromagnetic spectrum are fundamentally the same thing. They are all types of electromagnetic waves, differing from each other only in wavelength. Wavelength is the distance between one wave crest and the next. The longest wavelengths are radio waves, which can be the size of buildings. The shortest—gamma rays—are smaller than the nucleus of an atom.

Electromagnetic waves also can be described by their energy and frequency, and these characteristics are related to the others in a precise mathematical way. Thus, when describing the spectrum, scientists may refer to the energy of an x ray or the wavelength of a microwave or the frequency of a radio wave.

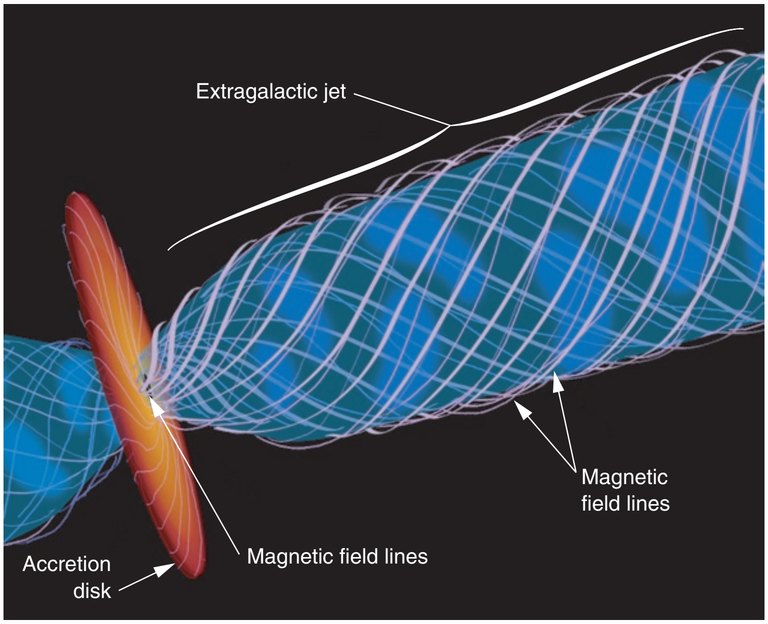
Electromagnetic radiation also consists of photons. These massless particles travel in a wavelike pattern and move at the speed of light. Each photon contains a certain amount, or bundle, of energy. The only difference between the various types of electromagnetic radiation is the energy of the photons, with radio waves at the low-energy end of the spectrum and gamma rays at the high-energy end.



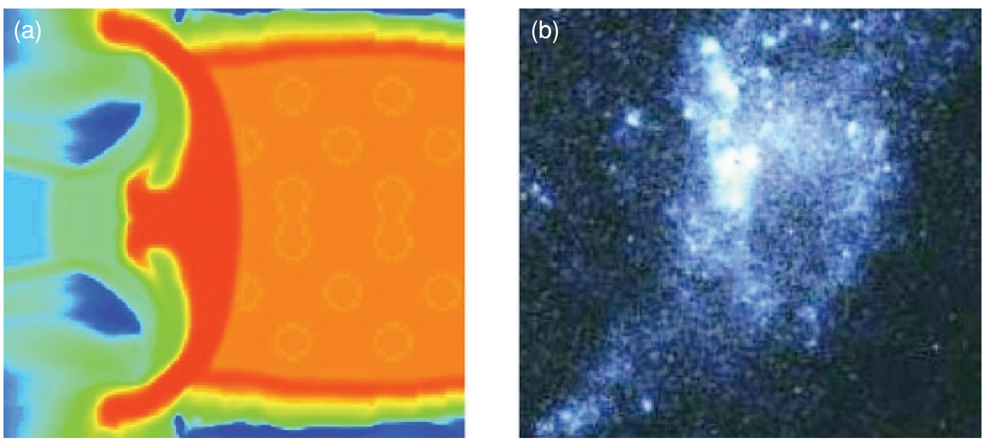
The distance between two adjacent wave crests of an electromagnetic wave is its wavelength.

Black Holes: Give and Take

For van Breugel, the discovery that black holes can give as well as receive is poetic justice. "Twenty years ago, we would have thought this idea was a fantasy," says van Breugel, whose fascination with black holes goes back to the 1980s. "The fact that these big, bad black holes can actually give birth to new stars is exciting."



Accretion disks rotating around black holes can be hundreds of light years across. The disk has a cold outer region and an ultrahot inner region and fuels black holes by feeding matter into them. Magnetic fields help collimate powerful radio jets that expel material from the accretion disk at high speeds.



A comparison of (a) an intermediate density distribution plot from numerical simulations with (b) a similarly scaled observation of Minkowski's Object shows clear similarities between the distribution of the postshock gas within the simulated cloud (red) and the regions of active star formation within Minkowski's Object.

Recent evidence shows that black holes are likely common objects at the centers of galaxies. A black hole is an object with so much mass concentrated in a relatively small area that its escape velocity—the velocity necessary for a nearby object to escape the hole's gravitational pull—is greater than the velocity of light. Thus, scientists reason, nothing near a black hole can escape its gravitational pull—not even light. Research suggests that black holes inhabiting the centers of powerful radio galaxies have billions of times the mass of the Sun and would fit within a space the size of the solar system.

Astrophysicists do not agree on the mechanisms involved when violent radio jets shoot out from the vicinity of a black hole. One leading theory involves the interaction of the magnetic fields generated by the accretion disks that rotate around supermassive black holes. An accretion disk is a giant ring of gas and dust and can be hundreds of light years across. The disk has a cold outer region and an ultrahot inner region that lies a few billion miles from the black hole. The accretion disk fuels the black hole by feeding matter into it. Through a process not fully understood, some gas in the disk is drawn out by magnetic fields, which creates the radio jets.

Radio Astronomy at Work

"According to our astronomical observations," says van Breugel, "energetic feedback by jets from active black holes can significantly affect the interstellar medium in galaxies in ways that had not been previously considered." Most theories of galaxy evolution assume that this black-hole feedback will slow down or shut off star formation. Van Breugel and Croft found that active black holes might occasionally have a positive effect that enhances star formation.

To better understand this effect, van Breugel also investigated the effects of high-energy particles on interstellar dust grains that control the efficiency of the star-formation process. Working with Livermore colleagues from the Chemistry and Materials Science and Physics and Advanced Technologies directorates, he began laboratory experiments irradiating interstellar dust analogs with high-energy particles.

Van Breugel notes that Livermore provides an excellent environment for the study of active black holes and their role in forming galaxies. "Gaining an understanding of the relationship between the radio jets and star formation requires complex, multidimensional numerical simulations," says van Breugel. He credits the computer modeling done with Livermore astrophysicist Peter Anninos's

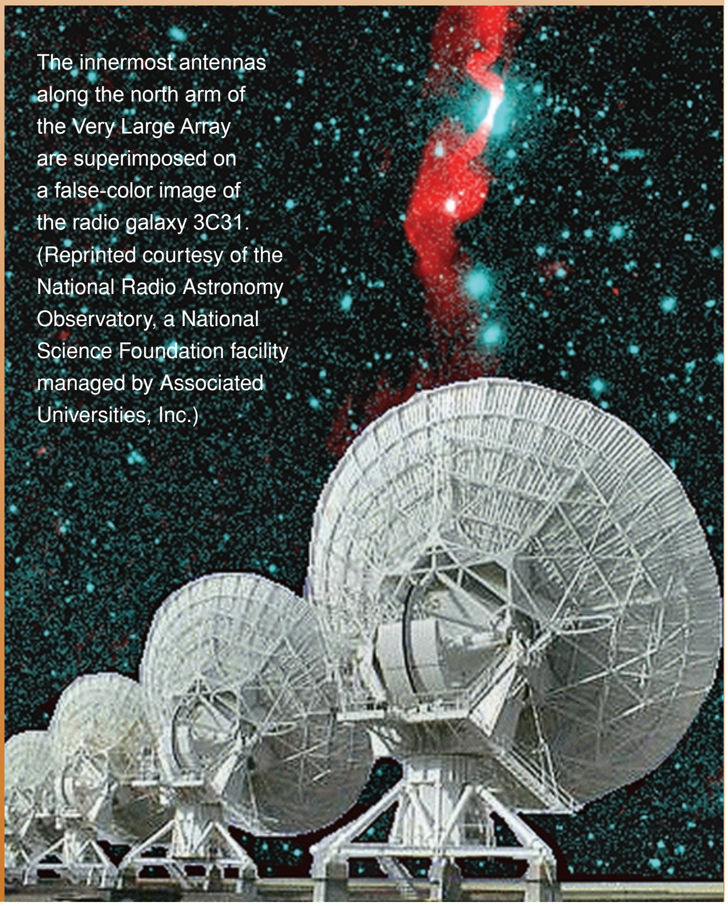
Give Me Land, Lots of Land: A Radio Astronomy Primer

Radio waves penetrate much of the gas and dust in space and pass through the terrestrial atmosphere with little distortion. Radio astronomers can therefore obtain a much clearer picture of stars and galaxies than is possible by means of optical observation, as long as they emit at radio wavelengths.

Radio telescopes work in much the same way as optical telescopes. Just as optical telescopes capture the visible light emitted from celestial objects, radio telescopes capture the electromagnetic radiation in the radio wavelength region. Radio telescopes comprise a large radio antenna and a sensitive radio receiver. The most common radio telescopes, such as those that make up the Very Large Array (VLA) near Socorro, New Mexico, look similar in design to a satellite television dish. Because cosmic radio sources are so weak, the parabolic dish that captures the incoming radiation must be very large and the radio receiver, or radiometer, must be highly sensitive. Signal-processing techniques are used to detect astronomical radio signals that can be as much as a million times weaker than the noise generated in the receiver.

Because radio waves are so long, the best possible telescope to capture them would be, perhaps, many kilometers in diameter. The physical constraints of designing and constructing such an instrument are obvious. By using a technique called interferometry, astronomers can capture the same results by grouping many instruments at some distance from one another and having them work together as if they were one instrument. The VLA is just such a telescope system. Its 27 individual radio antennas capture data that can be combined electronically so that the array effectively functions as one giant antenna. Although each antenna is only 25 meters in diameter, the combined data from the antennas gives the resolution of an antenna that is 36 kilometers across.

The world's largest and most powerful radio telescope to date is the Very Long Baseline Array (VLBA), a system of ten radio telescope antennas that are controlled remotely from the Array Operations Center in Socorro, New Mexico. The VLBA spans more than 5,000 miles with stations from Mauna Kea on the Big Island of Hawaii to St. Croix in the U.S. Virgin Islands. Each station has a dish antenna 25 meters in diameter, as well as a control building housing a computer, tape recorders, and other equipment for collecting the radio signals captured by the antenna. The VLBA provides the sharpest vision of any telescope—optical or radio—on Earth or in space.



The innermost antennas along the north arm of the Very Large Array are superimposed on a false-color image of the radio galaxy 3C31. (Reprinted courtesy of the National Radio Astronomy Observatory, a National Science Foundation facility managed by Associated Universities, Inc.)

COSMOS code for much of the direction the work on jet-induced star formation has taken. (See *S&TR*, March 2003, pp. 4–11.)

COSMOS, a massively parallel radiation-hydrodynamics code developed at the Laboratory, is easily adaptable to probe astrophysical problems. The code has been used to simulate such events as the development of accretion disks in black holes and the evolution of the universe. A key simulation for van Breugel and Croft's research was to predict the chemistry of an environment after radio jets collide with the interstellar medium.

COSMOS incorporates 27 chemical reactions, including both collisional and radiative processes for atomic hydrogen and helium gases as well as molecular hydrogen chains. With it, scientists can simulate the dynamics of the cooling of the gas cloud, a critical step in star formation. "If warm gas cools and produces neutral hydrogen that is dense enough, we should get star formation," says Croft. "The simulations showed that the presence of neutral hydrogen was, indeed, likely in the surrounding environment of Minkowski's Object, which was confirmed by our observations."

Both Croft and van Breugel point out that much more work is needed in the search to determine how the universe began. "It's not the end of the story," says van Breugel. "We have many complicated questions, and we'll need both observational data and simulations to find the answers."

For instance, van Breugel wants to use the COSMOS code to help determine the age of Minkowski's Object and the properties of the jets, which are relatively brief outbursts in the life of galaxies. "The only way to understand these things is to look at what's out there and figure out how jets interact with the interstellar medium," he says.

By combining computer simulations with both optical and radio astronomical techniques, van Breugel is certain that today's astrophysicists will find a few more answers and, certainly, many more questions for the next generation of scientists to pursue.

—Maurina S. Sherman

Key Words: accretion disks, black holes, COSMOS code, early universe, electromagnetic spectrum, gas clouds, Minkowski's Object, molecular hydrogen, nearby galaxies, NGC 541, neutral hydrogen, radio astronomy, radio emission, radio interferometry, radio jets, radio telescope, star formation, Very Large Array (VLA).

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